THE

JOURNAL OF GEOLOGY

JULY—AUGUST, 1900

IGNEOUS ROCK-SERIES AND MIXED IGNEOUS ROCKS

I. IGNEOUS ROCK-SERIES

BY an igneous *rock-series* we may understand an assemblage of rock-types, differing perhaps widely but still with a certain community of characters, associated in the same district and belonging to the same suite of eruptions, and further, holding a similar position in the scheme of igneous rocks belonging to that suite. Adopting the differentiation hypothesis, we may conceive them as derivatives of the same order from one common source, resulting from differentiation along similar lines and to the same degree. The fundamental characteristics of such a series, having regard to chemical composition, are of two kinds: (1) those belonging to the individual rock-types and shared by all the types included in the series (*e. g.*, each member is rich in some particular constituent, as compared with average igneous rocks of like silica-percentage); and (2) those belonging to the assemblage of types as a whole, depending upon variations in the composition of the members as compared with one another (*e. g.*, a particular constituent may in one rock-series fall off steadily with increasing silica-percentage, in another series it may rise to a maximum and then decline). These characteristics, and especially those which fall under the second head,

come out most clearly when exhibited graphically in a diagram such as was first used by Professor Iddings.[1]

The diagram is easily constructed from the analyses of the rocks (Fig. 1). Two rectangular axes, *OX* and *OY*, are drawn, horizontally and vertically, each of length equal to 100 parts of some convenient scale. We cut off the abscissa *OM* to represent the silica-percentage of any one of the rocks, and erect ordinates *MP*, *MQ*, etc., to represent the corresponding percentages of the other oxides, which we may conveniently speak of as the bases. This is done for each of the rocks. Then joining *P P'*. . . . ., etc., we have a line which represents the variation of one particular base in this rock-series, and similarly for the other bases. Iddings converts the figures of the analyses into molecular proportions before expressing them graphically; but for our present purposes nothing would be gained by doing this, and we may follow the simpler method.

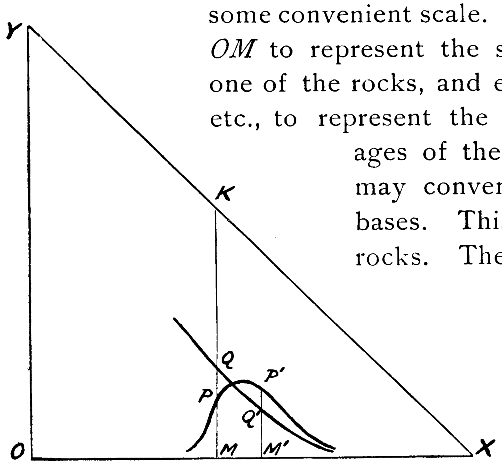

FIG. 1.

The lines *PP'*. . . . ., etc., *QQ'*. . . . ., etc., as thus laid down, are broken or zigzag lines. We find, however, that in a rock-series in the strict sense of Brögger the departures from regularity are not great. Minor irregularities may arise from the variation found among different specimens of the same rock-type, or from errors in the analyses. To obtain a clearer picture of the essential variations characteristic of the series it will be legitimate to *smooth* the lines, *i. e.*, to convert them into flowing curves passing as nearly as may be through the proper points. The diagram then affords a graphic representation of the chemical characteristics of the given rock-series. We may use it, for

[1] Origin of Igneous Rocks, Bull. Phil. Soc. Wash. (1892), Vol. XII, pp. 89–214.

example, to obtain by interpolation the chemical composition of a member of the series intermediate between two known members. To predict by extrapolation the composition of a hypothetical member beyond the limits covered by actual representatives is, of course, a more speculative matter, since we have no precise data for prolonging the empirical curves. There are, however, some obvious considerations. The sum of all the ordinates MP, MQ, etc., for a given rock must be equal to MK, K being the point in which the vertical through M meets the straight line YX. Hence all the curves must be contained within the triangle YOX : prolonged to the right, they must all meet at the point X, corresponding with a hypothetical rock with 100 per cent. of silica : prolonged to the left, they must meet the line OY in points such that the sum of all the ordinates is equal to OY, corresponding with a hypothetical rock devoid of silica.

The simplest kind of variation conceivable is found when, with increasing silica-percentage, the percentage of each base changes at a constant rate (different for each). In other words, the percentage of each base is then a linear function of the silica-percentage. Such a series may be termed a *linear series*, and its geometrical characteristic is that all the curves in the diagram become straight lines. In the wholly ideal case of a linear series extending to the ends of the scale, all these straight lines would decline towards the right and meet at the point X. It is safe to say that no such series exists in nature, nor has any natural series been described corresponding with a portion of such a diagram. It may, however be inquired whether, or to what extent, natural rock-series fulfill the condition of linearity within the limits of the actual representatives of the series. Professor Brögger, in his memoir on the grorudite-tinguaite-series,[1] makes approximate linearity a characteristic property of a *Gesteinsserie* : this is implied in his dictum "every mean of a number of members of the series corresponds approximately with a possible member of the series." But it is easy to show by plotting graphically the analyses which he gives that this

[1] Eruptivgesteine des Kristianiagebietes (1894), Part I, p. 175.

must not be understood in too literal a sense. Indeed, Brögger himself abandons the principle; for, in calculating by extrapolation the composition of a hypothetical end-member of the series, he supposes that, while some of the bases vary in arithmetical, others vary in geometrical proportion: a supposition inconsistent with linearity.[1] If a few rock-series be actually plotted in diagrams, it soon becomes apparent that, while some of the bases often give sensibly straight lines within the limits of the actual rocks, others give lines very decidedly curved. We may note in passing that some kinds of variation in igneous rock-masses connected with differentiation *in situ* involve much more considerable departures from the linear type. Such, for instance, is the "concentration" of the more basic constituents in certain parts of a rock-body, as investigated by Vogt and others.

It appears then that in general the diagram of a rock-series will consist of *curved* lines to indicate the variations in percentage amount of the several bases. Of these curves we may disdistinguish two kinds: (*a*) When the constituent in question first increases to a maximum and then decreases, or increases first more rapidly and then less rapidly, or decreases first less rapidly and then more rapidly, the curve will be *convex* upward; (*b*) When it decreases to a minimum and then increases, or decreases first more rapidly and then less rapidly, or increases first less rapidly and then more rapidly, the curve will be *concave* upward. This classification is not an exhaustive one, for there may be curves which are inflected, being convex in one part and concave in another, but it will be sufficient to consider the simpler cases. Since the sum of the ordinates for all the bases falls off steadily in linear fashion, its curve of variation being the straight line *YX*, it follows that in any series, other than an ideal linear one, some of the bases must give convex and others concave curves.

II. MIXED IGNEOUS ROCKS

Considerable differences in composition may exist among members of the same rock-series, and still greater differences are

[1] *Ibid.*, p. 172.

found among members of different series belonging to the same suite of eruptions in one district. Most of those who have discussed the origin of igneous rocks have sought the cause of this diversity in various processes of diffusion, etc., commonly spoken of as *differentiation* in rock-magmas; it is no part of our present object to discuss these processes. Some geologists, however, including Professor Sollas and Dr. Johnston-Lavis, have laid stress on the possible origin of certain igneous rocks by *admixture*, a process in some sense the reverse of differentiation, and this question we shall consider more closely.

We may distinguish *a priori* three cases:

1. Mixture of two fluid rock-magmas.
2. Permeation or impregnation of a solid rock by a fluid magma with consequent reactions between the two.
3. Inclusion of solid rock-fragments (xenoliths of Sollas) in a fluid magma and their partial or total dissolution and incorporation in the magma.

In the first case the two rocks involved must be of the same age and presumably from a common origin. In the second and third cases this is not necessarily true, and the solid rock need not even be an igneous one; but, when we examine actual instances which have been described, it seems probable that here also admixture does not in fact take place on an important scale except between igneous rocks of cognate origin. Lacroix, in his exhaustive memoir on xenoliths,[1] distinguishes two categories, *enclaves énallogènes*, which are not related in composition or by origin to the enclosing rock (*e. g.*, limestone fragments in trachyte), and *enclaves homœogènes*, which do present more or less resemblance in composition and origin to the rock in which they are enclosed (*e. g.*, olivine-nodules in basalt). Similarity of mineralogical composition is, however, by no means a sufficient test of community of origin among igneous rocks, and instances may easily be cited (*e. g.*, some cases of gabbro enclosed in granite) which would be placed by Lacroix under the former of his two heads, but in which there exists, despite differences of

[1] Les enclaves des roches volcaniques, Macon, 1893.

composition, an essential and close relationship between the two rocks thus associated. Instead of using the above terms in an altered sense, it will be better to coin new ones, and we shall accordingly recognize two kinds of xenoliths, *accidental* and *cognate*. This distinction is based, not on difference or likeness in composition, but on the existence, in the latter kind, of a genetic relationship between the enclosed and the enclosing rock, which is wanting in the former kind. A like distinction will apply to the permeation of a solid rock-body by a fluid magma. Now although both permeation and the incorporation of xenoliths are known in instances which fall under the accidental category, they are known thus only as quite local phenomena. If new rocks of any considerable extent or importance are actually produced by admixture, it is by admixture of two cognate rocks. One reason for this is doubtless to be found in the consideration that reactions between a solid rock and a fluid magma will be promoted by the former being still at a high temperature when the latter comes into contact with it. There may be other reasons of a chemical nature.

Without discussing at once whether admixture is a factor of prime importance in the genesis of igneous rocks, we may inquire what kind of rocks are to be expected from such a mode of origin. We take first the simplest case, that of admixture between two members of the same rock-series. The chemical composition of the resulting product will be the same whether both or only one of the two rocks be fluid at the time when they are brought together. If the series be a linear one, the admixture will produce a rock having the composition of a possible member of the series. This is Brögger's principle already quoted, which, however, requires to be limited by the condition here imposed. In the more general case the mixed rock will not correspond with a possible member of the series, but will differ more or less in composition from that possible member which has a like silica-percentage. This is clear when expressed graphically (Fig. 2). If OM and OM' represent the silica percentages of the two component rocks, and their proportions

in the mixture be a to b, then Om will represent the silica-percentage of the mixture, m being the point which divides MM' in the ratio b to a. (The empty portion of the diagram is omitted to save space.) If PpP' be the curve of variation of some one of the bases, then mp' in the figure represents the percentage of that base in the mixed rock. The percentage in the corresponding member of the rock-series is represented by mp, and the mixed rock is therefore deficient in this base as compared with the latter, the defect being represented by pp'. Similarly a different base, having QqQ' for its curve, will be in excess in the mixed rock as compared with the corresponding member of the rock series, the excess being represented by qq'. It is evident that there will be a defect or an excess according as the curve is convex or concave between the points corresponding with the two component rocks. The defect or excess will be greater, *ceteris paribus*, the farther apart the two component rocks are in the series. It is easy to see that, given a series such that its diagram has markedly curved lines, the result of the admixture of two members may be something not only foreign to the series, but highly peculiar by comparison with igneous rocks in general.

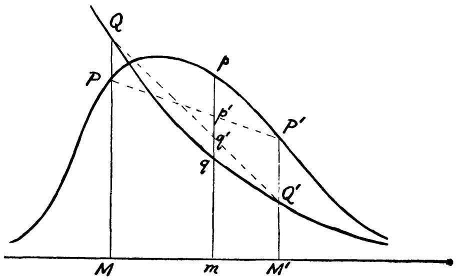

FIG. 2.

This may be still more strikingly the case in the admixture of two rocks which have no such close relation with one another. In illustration we take two simple cases of accidental xenoliths. First suppose a rock-magma to become enriched in silica by dissolving quartz, of extraneous origin, a parts of the magma taking up b parts of quartz. Dividing MX at m in the ratio b to a, we have Om to represent the silica-percentage of the resulting mixed rock (Fig 3). If MP, MQ, etc., represent the percentages of the various bases in the original magma, then mp', mq', etc., will represent them in the mixed rock, these ordinates being

cut off by straight lines joining the points *P*, *Q*, etc., to *X*. If we now draw curves such as *Pp*, *Qq*, etc., to indicate in a general way the usual behavior of the several bases in average igneous rocks, we obtain some idea of the respects in which the mixed rock is peculiar. In the diagram it is shown as being unusually poor in the first base and rich in the second. Next suppose a rock-magma to become enriched in lime by dissolving limestone, in the proportion of *a* parts of the magma to *b* parts of lime. The result is illustrated by the diagram, Fig. 4. The line *OM* is divided at *m* in the ratio *a* to *b*. If *MP* represents the lime in the original magma, *mp′* will represent that in the mixture, this ordinate being cut off by the straight line joining *P* to *Y*. If *MQ* and *MR* represent two other bases in the original magma, *mq′* and *mr′* will represent them in the mixture, these ordinates being cut off by straight lines joining the points *Q* and *R* to *O*. It is noteworthy that the mixture, as compared with ordinary igneous rocks, may be unduly rich in other bases besides lime: in the figure this is the case with the second of the two bases represented (curve passing through *R*).

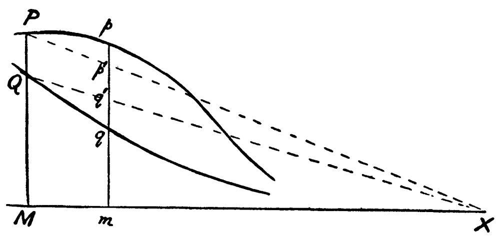

FIG. 3.

The foregoing general considerations lead us to anticipate that a rock resulting from admixture may be, and in many cases must be, of peculiar chemical composition. A rock-series, for example, may consist of basalt, pyroxene-andesite, dacite, and rhyolite; but it does not follow that a mixture of basalt and rhyolite will produce an andesite or a dacite. Still less will a basalt be converted into an andesite by addition of silica, or a rhyolite into a dacite by addition of lime. The processes by which different igneous rocks have been evolved from a common stock are too complex and subtle to be reversible, at least by so crude a method as that of admixture. To illustrate these remarks from

actual instances, we have only to take a collection of trustworthy rock-analyses, such as that published by Clarke and Hillebrand,[1] and plot diagrams upon a convenient scale. The lavas of the Lassen Peak region in California afford a good example. Here the curves of some of the bases approximate to straight lines throughout a considerable part of their extent. Towards the basic end, however, the alumina-line becomes strongly convex and those for magnesia and lime decidedly concave, while the soda-line is slightly but distinctly convex throughout. This diagram includes the normal basalts, andesites, dacites, and rhyolites; and the very slight amount of smoothing required to obtain flowing curves stamps this group of rocks as a natural series. The quartz-basalts, on the other hand, refuse to adapt themselves to this scheme, and their abnormal composition is clearly brought out by plotting their analyses on the same diagram. In their content of lime and potash they do not differ notably from normal rocks of like silica-percentage, but they show a marked deficiency in alumina and ferric oxide, and to a less degree in soda, and an excess of magnesia and ferrous oxide.

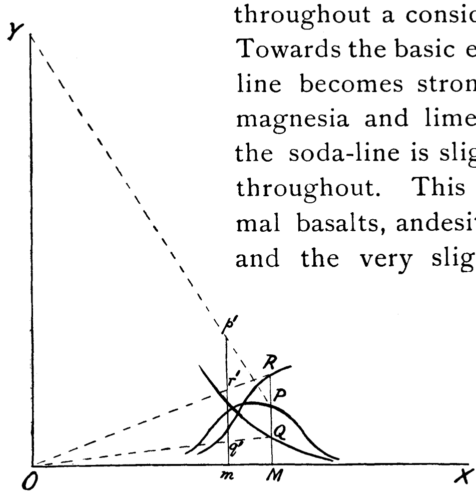

FIG. 4.

Although natural series of igneous rocks differ considerably from one another, they nevertheless possess certain broad characteristics in common. This is recognized by the very general practice of speaking roughly of acid, intermediate, and basic rocks, etc., as having more or less distinctive characters; which tacitly assumes that, in the broadest view, they fall approximately into a single line. Given a large number of analyses of normal (unmixed) igneous rocks, we might average the composition of those having like silica-percentages, and construct

[1] Analyses of Rocks, Bull. No. 148, U. S. Geol. Surv. 1897.

from such averages a diagram expressing the variation of the several bases. Further, we might note the limits of variation of each base within each group averaged, and express these limits also on the diagram. Each base would therefore be represented, not by a simple curve, but by a curved band of varying width. A still further refinement would be to indicate, say by different depths of color within the bands, the frequency of different degrees of departure from the average. On such a diagram it would be possible to test with some precision the principle here advanced, that mixtures, even of two normal igneous rocks and still more of an igneous and a sedimentary rock, must often be abnormal in chemical composition.

So much labor is, however, not necessary for our present purpose. We have hitherto considered only the bulk analyses of the rocks; but we know that a close relation exists between the chemical composition and the mineralogical; a relation which is a matter of very nice adjustment. Expressing it in a crude empirical way, we may say that the chemical variation evinced in normal igneous rocks is not of an arbitrary kind, but is such that the rock-magmas have been able to crystallize as mineral-aggregates consisting of species selected from a comparatively small category, and selected subject to certain laws of paragenesis which control the permissible associations of those mineral species. In a natural assemblage of rock types, whether a "Gesteinsserie," a "Faciessuite," or any other kind of grouping, the limitations are of course narrower still. To inquire into the significance or rationale of such rules would be to enter upon a theoretical discussion of the processes of differentiation, a subject outside our scope: they are introduced here as affording in great measure a test for mixed igneous rocks. For it follows that any variation of an *arbitrary* kind (*i. e.*, not on the lines of magmatic differentiation) imposed on the *chemical* composition of an igneous rock-magma may produce much more considerable modification in the *mineral* composition of the resulting rock. It is well known that, when a magma has absorbed material from sedimentary rocks, this often results in the formation of such

minerals as cordierite, sillimanite, corundum, spinel, idocrase, and others, which are either quite foreign to normal igneous rocks or at least foreign to rocks of the general type of those concerned. A mixture of two igneous rocks will in general show less obvious peculiarity, but it may still be expected to betray itself in the occurrence of unusual minerals, unusual mineral-associations, or unusual relative proportions of the constituent minerals. That it often does so betray itself in a fashion quite unmistakable, is proved by numerous examples of undoubted mixed rocks which have come under the notice of the present writer.

The question here broached has a very direct application to a subject now much in the minds of petrologists, viz., the endeavor to arrive at some natural (as opposed to a merely Linnæan) classification of igneous rocks. Such a classification must be based, confessedly or implicitly, upon fundamental genetic considerations, and primarily upon the mode of operation of the processes of differentiation in rock-magmas. Rocks resulting from admixture must therefore be excluded from the main scheme and relegated to an appendix. Any discussion which tends to the recognition of this principle and to the establishment of some criterion of distinction will forward the object by disembarrassing the problem of a disturbing element.

ALFRED HARKER.